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On the Differential Cross Section for Neutron-Proton Scattering at 14.1 MeV

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Abstract

The revised data of the n-p differential cross section at 14.1 MeV have been presented. The new values of the cross section at 8 mean neutron-scattering angles in the range 172.0^{o} - 52.5^{o} in the C.M. system have been increased systematically by about 2.3% than our previous values due to the neutron flux correction calculated precisely. The result of a re-measurement done by changing a polyethylene radiator and a neutron-source apparatus is in good agreement with the revised data.

1. Introduction

In a previous paper[1], we presented our result of the differential cross section for scattering of 14.1 MeV neutrons by protons, which was measured at 8 setting angles of a counter telescope in the range $\theta_o = 0^{o} - 64^{o}$. The value of the cross section for each angle was obtained in reference to the absolute value of cross section 233.6 ± 3.2 mb/sr determined at $\theta_o = 0^{o}$ in which the mean proton-recoil angle $\bar{\theta}_p = 4.0^{o} \pm 2.3^{o}$ in the laboratory system. In this determination of the absolute value of cross section, we have somewhat roughly corrected for energetically degraded neutrons and the incident neutron flux, and estimated the systematic errors for the determination as ±1%, ±1.5% and ±1% in the standard deviation for uncertainties in radiator thickness, neutron flux and experimental geometry, respectively. After that, we re-measured the cross section by changing a $(CH_2)_n$ radiator and a target apparatus of the T-d neutron source as well as by improving the electronic system, in the cource of our n-d break-up experiments[2,3], and re-analyzed both our data by doing a careful flux determination especially. In this note, we describe the procedure of the neutron flux correction and our revised results on the n-p differential and total cross sections at 14.1 MeV.

2. Experimental and Corrections

The thicknesses of $(CH_2)_n$ radiators used in our previous work[1)] (say the ^{1}H-#3 target) and in the present one (say the ^{1}H-#5 target) are 5.34 ± 0.05 mg/cm^2 and 8.29 ± 0.03 mg/cm^2, respectively. Polyethylene of the ^{1}H-#5 target was prepared by radiation-polymerization, and the purity was 1.9999 in ^{1}H/C. The uniformity of the radiators was observed by scanning with a microscope to be within about ±3% of the above averaged thicknesses in the central area of 1.2 cm in diameter.

The experimental geometry is the same as that described[1)] previously. The T-d neutron-source apparatus following a Cockcroft-Walton accelerator (say the Mark II for the present apparatus while the Mark I for the previous one) has been designed so that a T-Ti-Cu target is movable for keeping a neutron yield to be almost constant without changing the position of neutron-source point. The thicknesses of some parts of the apparatus working as scatterers for incident neutrons are seen in Table I.

The corrections for the net neutron flux at the radiator consist of (1) the direct total attenuation of 14.1 MeV incident neutrons produced at the source point by the T-Ti-Cu base (say Scatterer 0), two apparatus walls (Scatterers I and II), the telescope wall (Scatterer IV) and the radiator base (Scatterer V), (2) the elastic in-scattering of the neutrons by the scatterers, and (3) the counting correction of the α-monitor (a p-n junction Si-detector with a collimator of 2 mm in diameter) used for counting α-particles associated with the T-d neutrons.

In the computation for the above (1) and (2), we have used the total and differential cross sections[4,5,6,7] for elastic and nonelastic scattering by apparatus materials as the input data, and assumed that elastically scattered neutrons which can produce detectable recoil protons emitted at smaller angles than the maximum proton angle θ_p^{max} with respect to the direction of the neutrons are regarded as the "incident" neutrons. This angular width ($\sim 15^o$) corresponds to the maximum energy width of 1 MeV chosen in our determination of the cross section from the recoil proton spectrum measured at $\theta_o = 0^o$.

In the in-scattering flux correction (2) for the Scatterer II for instance, which is essentially a calculation of solid angles, the differential fraction of the number of neutrons $\Delta n_s(\theta_n)$ scattered into a solid angle $\Delta\Omega_2 = r_2\Delta r_2\Delta\phi_2\cos\theta_2/l_2^2$ about θ_n and contributed to produce recoil protons in the limited region $0^o \leq \theta_p \leq \theta_p^{max}$ to the number of neutrons n_o being incident directly into the maximum solid angle Ω_o subtended to the radiator from the neutron-source point was calculated as

$$\frac{\Delta n_s(\theta_n)}{n_o} = \frac{Nx}{\Omega_o}\,\frac{R_1\Delta\phi_1\Delta a\cos\theta_1}{l_1^2}\,\sigma_{el}(\theta_n)\frac{r_2\Delta r_2\Delta\phi_2\cos\theta_2}{l_2^2}\,\frac{S}{\pi R_3^2}\,, \qquad (1)$$

where N is the number of atoms in unit volume of the scatterer, $\sigma_{el}(\theta_n)$ is the differential cross section for neutron elastic scattering by the scatterer, other notations of constants and variables are given in Fig. 1, and

$$S = \tfrac{1}{2}({r_3^{max}}^2 - {r_3^{min}}^2)(\phi_3^{max} - \phi_3^{min}) \qquad (2)$$

in terms of the maximum and minimum values of r_3 and ϕ_3 on the detector window which are determined at every fixed values of a, ϕ_1, r_2 and ϕ_2 on the scatterer and the radiator. S varies from

πR_3^2 in a large part to 0. Then the total fraction F was obtained by the numerical integral of Eq. (1) with respect to the variables a, ϕ_1, r_2 and ϕ_2.

Fig. 1.

Here we note briefly on the determination of the cross section $\sigma(\overline{\theta}_p)$ where $\overline{\theta}_p$ is the mean proton angle calculated as

$$\overline{\theta}_p = \int_0^{\theta_p^{max}} \theta_p W(\theta_p)d\theta_p \Big/ \int_0^{\theta_p^{max}} W(\theta_p)d\theta_p . \tag{3}$$

$W(\theta_p) = \sigma(\theta_p)G(\theta_p)$ is the angular frequency distribution-function obtained from the solid-angle calculation under the condition of $\theta_p = \theta_p(r_2, \phi_2, r_3, \phi_3)$ = constant, in a similar way as those described by Voitovetskii, Korsunskii and Pazhin[8], and using tentatively the angular distribution shape of $\sigma(\theta_p)$ of Gammel[9]. Instead of obtaining the cross section averaged over 0^o to θ_p^{max} through

$$\overline{\sigma(\theta_p)} = \int_0^{\theta_p^{max}} \sigma(\theta_p)G(\theta_p)d\theta_p$$

from the measured proton spectrum $dC_m/dE_p = (dC_m/d\theta_p)(d\theta_p/dE_p)$, we have calculated $\sigma(\overline{\theta}_p)$ as

$$\sigma(\overline{\theta}_p) = \frac{C_m}{N_p V_p \Phi \Omega_3} , \tag{4}$$

where N_pV_p is the number of hydrogen in the radiator, $\Phi = \Phi_0(1 + F)$ is the incident neutron flux corrected for the attenuation and in-scattering in which Φ_0 is evaluated at the centre of the radiator, and Ω_3 is the effective solid angle of the telescope (5.526×10^{-3} sr) which is

$$\Omega_3 = \frac{1}{\pi R_2^2} \int_0^{R_2} dr_2 \int_0^{2\pi} d\phi_2 \int_0^{R_3} dr_3 \int_0^{2\pi} d\phi_3 \frac{1}{1+(r_2/D_0)^2} \frac{D_0}{l_0} \frac{r_2 r_3}{l_p^2} \frac{D_t}{l_p} . \quad (5)$$

In the derivation of Eq. (4), we have assumed that $\sigma(\theta_p) \simeq \sigma(\bar{\theta}_p)$ = constant in the region $0^\circ \leq \theta_p \leq \theta_p^{max}$ and ignored the correction term for F, which is derived in the expansions of $l_2 = l_2(a,\phi_1,r_2,\phi_2)$ and $l_p = l_p(r_2,\phi_2,r_3,\phi_3)$, because of the present fine geometrical parameters (D_0 = 11.2 cm, D_t = 14.3 cm and $R_2 = R_3$ = 0.6 cm) and a small value of F (several percent).

For other parts working as scatterers except the Scatterer I, Eq. (1) has been slightly modified due to the different shape of each scatterer, but the essential method of calculation is the same.

The aperture of the α-monitor has been defined with a collimator of 2 mm in diameter, which was placed 31.65 cm for the Mark I and 31.57 cm for the Mark II of the T-d neutron-source apparatus. In order to reduce the geometrical error since this diameter is small, we have calibrated both systems by using a 4 mm-dia collimator at 63.21 cm. In the α-counting correction (3), in addition to the above collimator correction we made corrections for counting excess due to the reactions Si(n,α)Mg and Si(n,p)Al produced in the α-monitor and for counting loss in the electronic system used.

Detailed results of the whole corrections for the net flux determination are given in Table I.

Table I.

3. Results and Discussion

In the previous work[1)] using the Mark I neutron-source apparatus and the ^{1}H-#3 target, the net flux correction has been disregarded because of the accidental cancellation by somewhat rough estimations of the in-scattering flux correction and the α-counting correction. Consequently, the previous values of the n-p differential cross section[1)] have been obtained as smaller values by 2.28%, which must be systematically corrected. The revised value of the cross section at $\bar{\theta}_p = 4.0^\circ$ in the laboratory system is 238.9 ± 4.0 mb/sr. In the present re-measurement using the Mark II and the ^{1}H-#5 target, we obtained $\sigma(\bar{\theta}_p=4.0^\circ) = 241.4 \pm 3.9$ mb/sr, which is in good agreement with the revised previous value within the over-all probable errors. The over-all error consists of the statistical error (±1.0%) and the systematical error (±1.3%) including uncertainties in the radiator thickness (±0.25%), the geometry (±0.7%) and the neutron flux (±1.1%) in the present case.

Our revised data of the n-p differential cross section at 14.1 MeV are summarized in Table II. The results of a least-squares fit

Table II.

are expressed as

$$\sigma(\Theta_n) = 54.1\ (1 - 0.0639 \cos \Theta_n + 0.0288 \cos^2\Theta_n)\ \text{mb/sr}$$

for the C.M. differential cross section and as $\sigma_t = 686 \pm 11$ mb for the total cross section. This value of σ_t is in good agreement with the value (689 ± 5 mb) of Poss, Salant, Snow and Yuan[10)]. Hence the discrepancy of 2.6% mentioned in our previous paper[1)] was solved by the neutron flux correction. Figure 2 shows our revised data for the C.M. differential cross section in comparing with our old one[1)], as well as with the data of other authors[11-15)] in which Basar's data[15] is that measured at 14.4 MeV.

Fig. 2.

It is found that our new data on the differential cross section agree well with the Nakamura data[13] in the backward hemisphere rather than the Los Alamos data[11,12]. In consequence of the present revision, our data became consistent with the time-of-flight data of Suhami and Fox[14] in the forward hemisphere. Also the present value of total cross section is consistent with the recent data of David and Barschall[16], as was so[2] for the n-d elastic case.

Since the present revision was made only due to the neutron flux correction, the discussion on anisotropy in the backward hemisphere and asymmetry about 90° in the comparison with the calculation based on the pion theoretical potentials is not quite changed from that given previously[1].

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Table I. Details of the neutron flux correction.

T-d neutron-source system number:	MARK I	MARK II
Target-collimator(2mmϕ) distance:	316.5 ± 0.5 mm	315.7 ± 0.5 mm
Total thickness for attenuation:	6.46 mm	3.16 mm
(1) T-Ti-Cu target base (0)	0.30 mm (Cu)	0.30 mm (Cu)
(2) Source box inner wall (I)	1.90 mm (brass)	0.60 mm (Fe)
(3) Source box outer wall (II)	3.00 mm (brass)	1.00 mm (Fe)
(4) Telescope wall (IV)	0.90 mm (brass)	0.90 mm (brass)
(5) Radiator base (V)	0.36 mm (Au)	0.36 mm (Au)
Total attenuation of flux:	-13.70 ± 0.33 %	- 6.70 ± 0.20 %
In-scattering total:	+ 8.05 ± 0.43 %	+ 3.96 ± 0.21 %
(1) Scatterer 0 (target base)	0.16 ± 0.02 %	0.16 ± 0.02 %
(2) Scatterer I (inner wall)	1.05 ± 0.11 %	0.55 ± 0.06 %
(3) Scatterer II (outer wall)	2.81 ± 0.28 %	0.96 ± 0.10 %
(4) Scatterer III(ring)*	2.59 ± 0.26 %	0.86 ± 0.09 %
(5) Scatterer IV (telescope wall)	1.43 ± 0.15 %	1.43 ± 0.15 %
Net flux attenuation:	- 5.65 ± 0.54 %	- 2.74 ± 0.29 %
α-monitor collimator correction:	+ 2.71 ± 0.20 %	+ 2.71 ± 0.20 %
α-monitor counting excess due to Si(n,α) and (n,p) reactions:	- 1.35 ± 0.50 %	- 1.35 ± 0.50 %
α-monitor counting loss:	+ 2.01 ± 0.20 %	+ 2.01 ± 0.20 %
Net flux correction:	- 2.28 ± 0.79 %	+ 0.63 ± 0.65 %

* The Scatterer III is a brass ring by which the T-Ti-Cu target was fixed.

Table II. 14.1 MeV n-p scattering data revised due to the neutron flux correction.

θ_o: the setting angle of the counter telescope.

$\bar{\theta}_p$ and $\sigma(\bar{\theta}_p)$: the mean proton-recoil angle and the differential cross section in the laboratory system.

$\bar{\Theta}_n$ and $\sigma(\bar{\Theta}_n)$: the mean neutron-scattering angle and the differential cross section in the centre-of-mass system.

θ_o (deg)	$\bar{\theta}_p$ (deg)	$\sigma(\bar{\theta}_p)$ (mb/sr)	$\bar{\Theta}_n$ (deg)	$\sigma(\bar{\Theta}_n)$ (mb/sr)
0.0	4.0±2.3 *)	238.9 ± 4.0 **)	172.0±4.6 *)	59.9 ± 1.0 **)
10.0	$10.4^{+4.3}_{-4.4}$	228.9 ± 3.7	$159.2^{+8.6}_{-8.8}$	58.2 ± 0.9
20.0	$20.1^{+4.3}_{-4.4}$	215.2 ± 3.7	$139.8^{+8.6}_{-8.8}$	57.3 ± 1.0
30.0	$29.9^{+4.2}_{-4.3}$	193.9 ± 3.4	$120.1^{+8.4}_{-8.6}$	55.9 ± 1.0
40.0	39.8±3.9	167.7 ± 3.3	100.3±7.8	54.6 ± 1.1
50.0	$49.8^{+3.6}_{-3.7}$	140.4 ± 3.1	$80.4^{+7.2}_{-7.4}$	54.4 ± 1.2
59.0	$58.8^{+3.2}_{-3.3}$	108.4 ± 2.8	$62.5^{+6.4}_{-6.6}$	52.3 ± 1.4
64.0	63.7±3.3	93.2 ± 2.7	52.5±6.6	52.6 ± 1.5

*) The values indicated with ± are the half-widths of the angular resolution functions.

**) The values indicated with ± are the over-all probable errors including the systematic errors.

Figure Captions

Fig. 1. Geometry of the Scatterer II (the outer wall of the neutron-source vacuum box) and the counter telescope for the calculation of the neutron flux correction. The distance between the neutron-source point and the centre of radiator D_0 = 11.2 cm, the distance between the centres of radiator and dE/dx-detector D_t = 14.3 cm, and the radii of radiator and detector-window $R_2 = R_3$ = 0.6 cm.

Fig. 2. Comparison between the present data on the n-p differential cross section $\sigma(\Theta_n)$ in the C.M. system and those of refs. 1, 11, 12, 13, 14 and 15). The curves are the results of least-squares fits to our present and previous data.

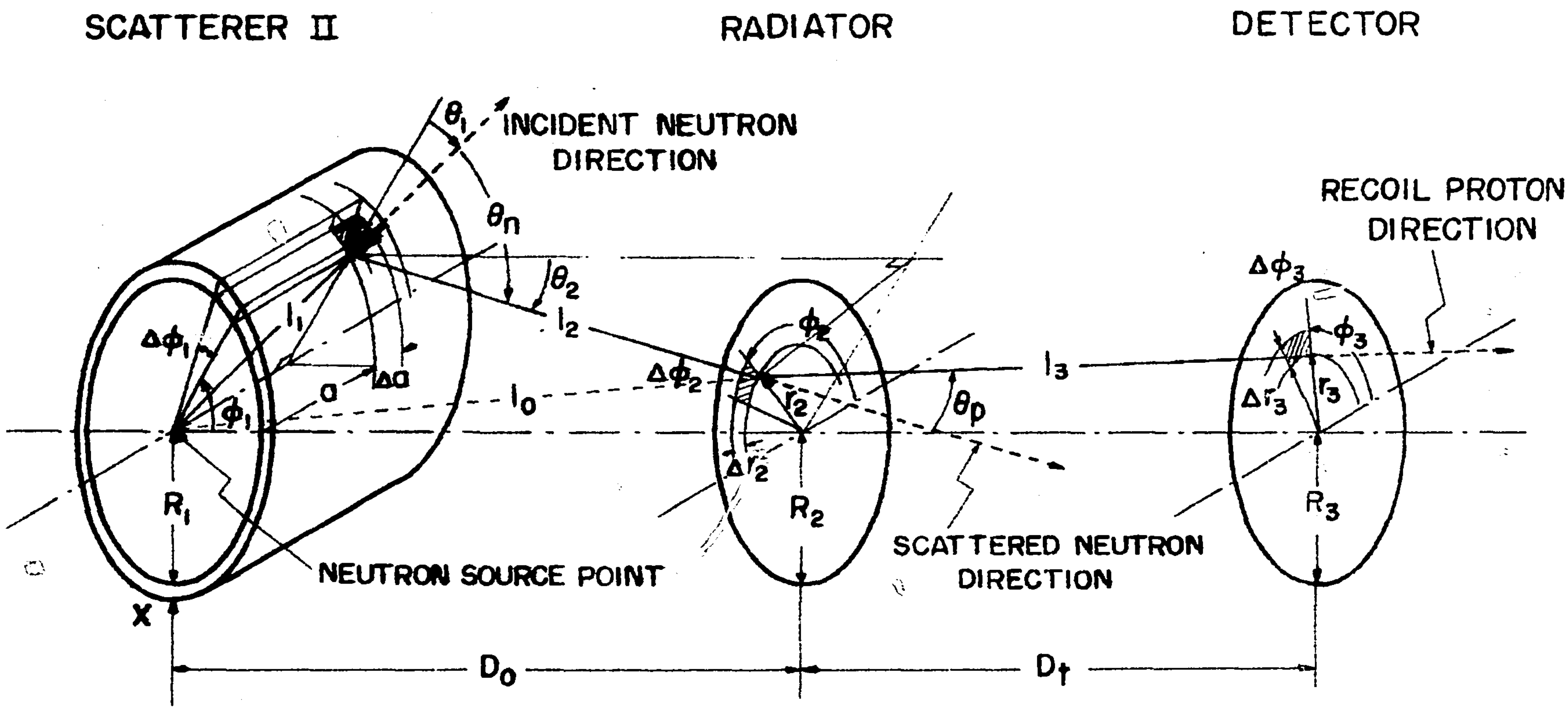
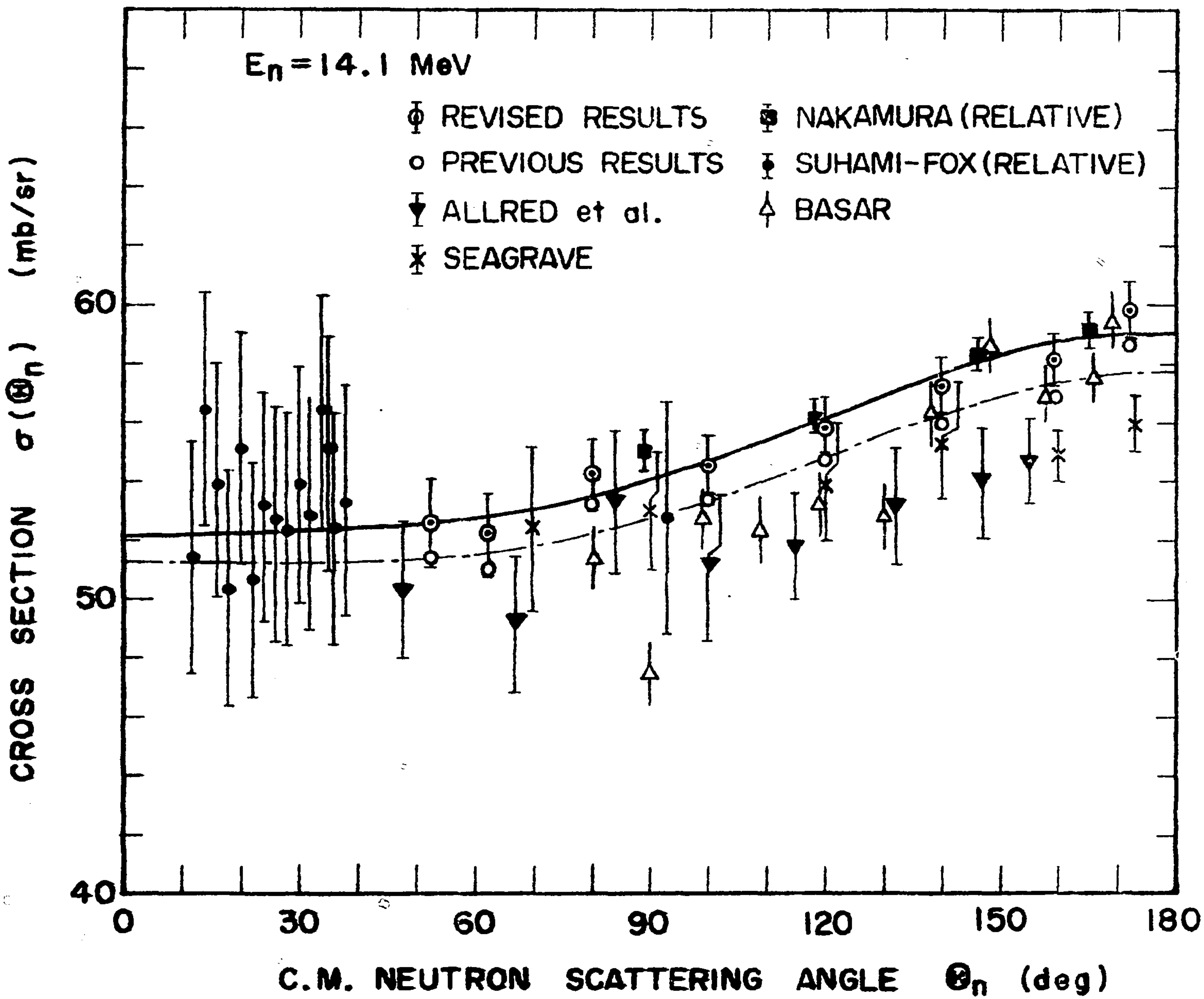

SCATTERER II
RADIATOR
DETECTOR
INCIDENT NEUTRON DIRECTION
RECOIL PROTON DIRECTION
SCATTERED NEUTRON DIRECTION
NEUTRON SOURCE POINT
θ_1
θ_n
θ_2
θ_p
l_1
l_2
l_0
l_3
$\Delta\phi_1$
ϕ_1
$\Delta\phi_2$
ϕ_2
$\Delta\phi_3$
ϕ_3
a
Δa
r_2
Δr_2
r_3
Δr_3
R_1
R_2
R_3
X
D_0
D_f

Fig. 1



$E_n = 14.1$ MeV
REVISED RESULTS
PREVIOUS RESULTS
ALLRED et al.
SEAGRAVE
NAKAMURA (RELATIVE)
SUHAMI-FOX (RELATIVE)
BASAR
CROSS SECTION $\sigma(\Theta_n)$ (mb/sr)
40
50
60
0
30
60
90
120
150
180
C.M. NEUTRON SCATTERING ANGLE Θ_n (deg)

Fig. 2